SLOT LINE INVESTIGATIONS

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THESIS

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by

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B.E.E. Marquette University, 1968

ABSTRACT

The slot line, since it was first proposed by Cristal et al [Ref. 1] in 1968, has been the subject of a continuing research effort in the microwave field. Some of this research effort is described herein, including difficulties encountered in slot line fabrication, and the design and construction of a slot line VSWR jig. Measurements of slot wavelength are presented with a comparison made to theoretical values. The results of VSWR measurements are also presented. Experimental work was performed in the 1GHz to 12GHz frequency range.

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ACKNOWLEDGEMENTS

The author wishes to thank Professor J. B. Knorr who suggested the topic and who offered several valuable suggestions in the course of the work. Thanks is also extended to the Naval Postgraduate School Machine Facility for the construction of the VSWR Jig, and to the many other departments here at the School who gave their assistance.

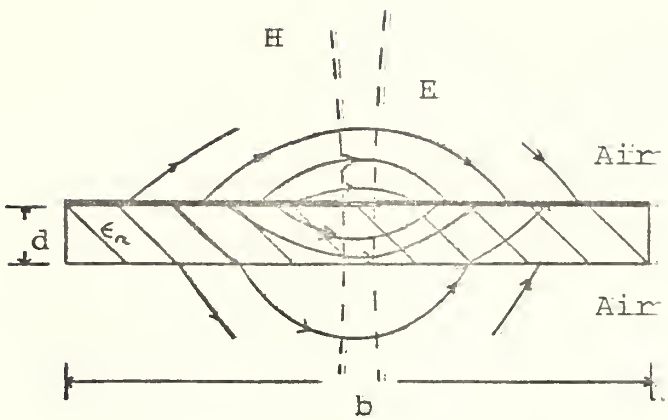
I. INTRODUCTION

The slot line, illustrated in Fig. 1, has been proposed by S. B. Cohn and others [Refs. 2, 3] as an alternative to microstrip for use in microwave integrated circuit design. A more recent proposal, the sandwich slot line is shown in Fig. 2.

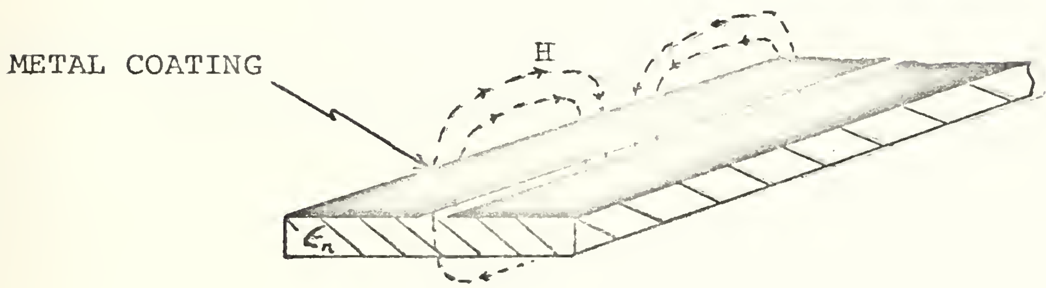
The TE nature of the slot wave suggests the possibility of connecting circuit elements such as diodes, resistors and capacitors in shunt with the slot. It should also be feasible to design filters and directional couplers with slot line techniques [Ref. 4].

The elliptical polarization of the H field suggests the possibility of circulators, isolators, and phase-shifters when the slot line is used with ferrites [Ref. 3].

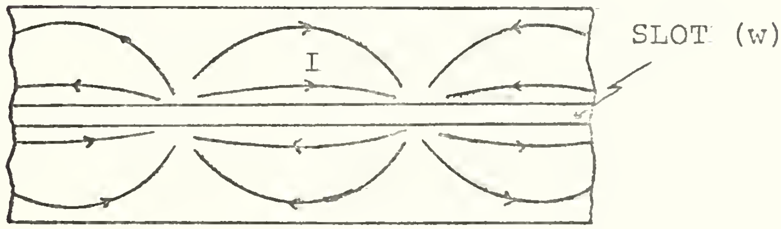
Before any of the above suggested applications can be successfully implemented, a more thorough investigation of slot line characteristics is needed. The original intent of this Thesis was to design a device for the direct measurement of slot line VSWR regardless of transition or termination used. While a device was eventually designed and constructed that would measure the slot line VSWR, of necessity slot line construction techniques became a major and time consuming part of the work done in the Thesis.



(a) E Field



(b) H Field



(c) Current Distribution on Metal Surface

Figure 1. Slot Line Fields and Currents.

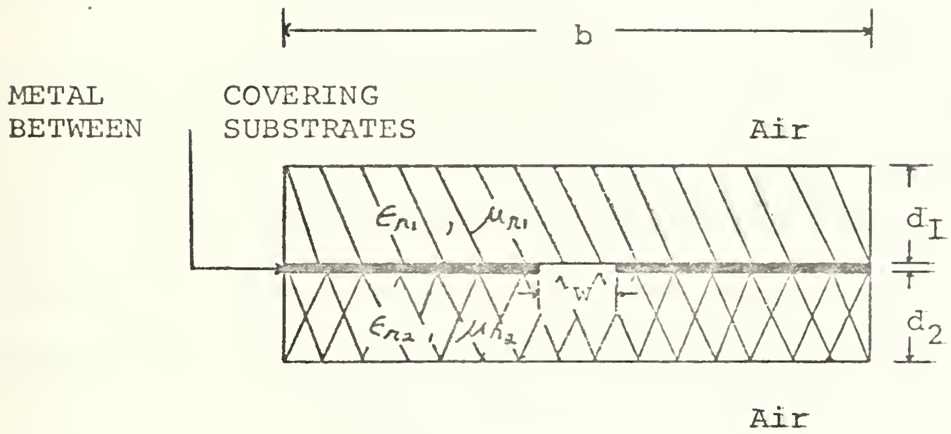


Figure 2. Sandwich Slot Line Cross-Section.

II. SLOT LINE THEORY

Slot line theory to date consists of a simplified zero-order solution and a more rigorous second-order solution to the slot line problem. These solutions were both developed by Cohn [Ref. 2].

A. USE OF THE ZERO-ORDER SOLUTION

The most important result of the zero-order solution is Eq. 1 which shows that the transmitted energy is tightly confined in the vicinity of the slot when the slot is constructed on a high permittivity substrate.

$$\frac{V(r)}{V_o} = \frac{\pi}{2} \cdot |k_c r| \cdot |H_1^{(1)}(k_c r)| \tag{1}$$

where:

$$k_c = \frac{j2\pi}{\lambda'}\sqrt{1-\left(\frac{\lambda'}{\lambda}\right)^2} \tag{2}$$

λ' is the slot wavelength and $H_1^{(1)}(j|x|)$ is the Hankel function of the first kind and order one with an imaginary argument.

Figure 3 shows a plot of 20 log $\left(\frac{V(r)}{V(o)}\right)$ versus radial distance "r" in inches from the slot, for a substrate with a dielectric constant of 20 and the zero-order value of k_c at 1GHz, 6GHz, and 12GHz.

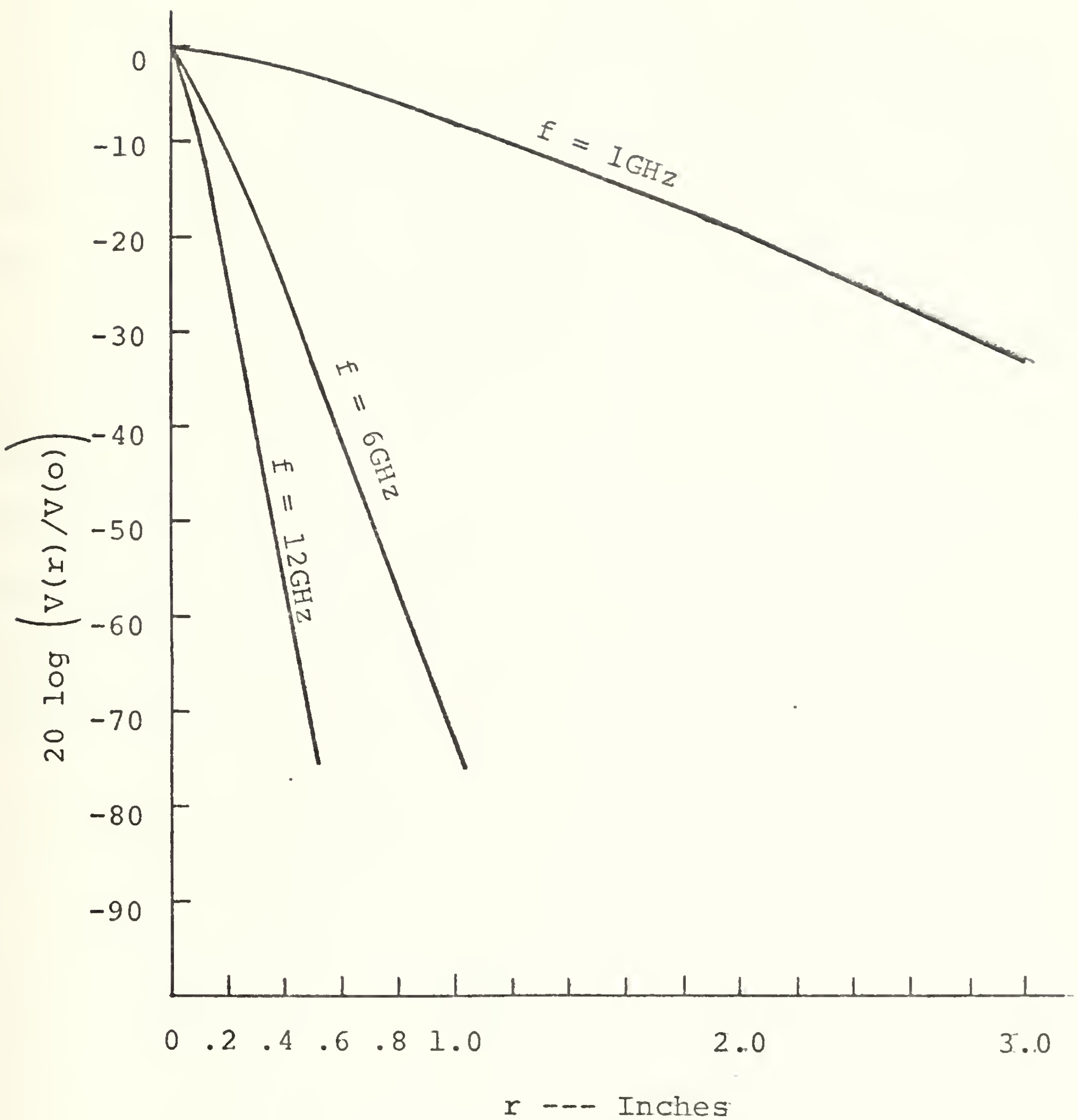


Figure 3. Plot Showing How the Slot Wave is Confined to the Vicinity of the Slot for $\varepsilon_r = 20$.

B. SOME RESULTS OF THE SECOND-ORDER SOLUTION

The second-order solution while more complicated is also more accurate than the zero-order solution. Figure 4 illustrates the boundaries and coordinates which were used to resolve the slot line into a capacitive iris and dielectric slab in a rectangular waveguide. This is the configuration upon which the second-order solution is based.

The solution was developed by placing conducting walls at x=0 and x=a, (the metal coating and substrate were assumed to be lossless) and then either electric walls or magnetic walls were placed at $y=\pm b/2$ (b greater than λ' for typical slot line). Equation 3 was then developed for the total susceptance (B_t) at the iris plane assuming electric walls at $y=\pm b/2$.

$$\eta B_t = \frac{a}{2b}\left[- v + u \tan\left(\frac{\pi d u}{a p} - \tan^{-1}\frac{v}{u}\right)\right] + \frac{1}{p}\left\{\left(\frac{\varepsilon_r + 1}{2} - p^2\right) \ln\frac{2}{\pi\delta} + \frac{1}{2} \sum_{n=1,2,3,\ldots} \left[v^2\left(1 - \frac{1}{F_n}\right) + M_n\right] \frac{\sin^2(\pi n\delta)}{n\,(\pi n\delta)^2}\right\} \qquad (3)$$

Where:

$p=\lambda/2a$ (the independent variable)

or $p=\lambda/\lambda'$ for $B_t=0$

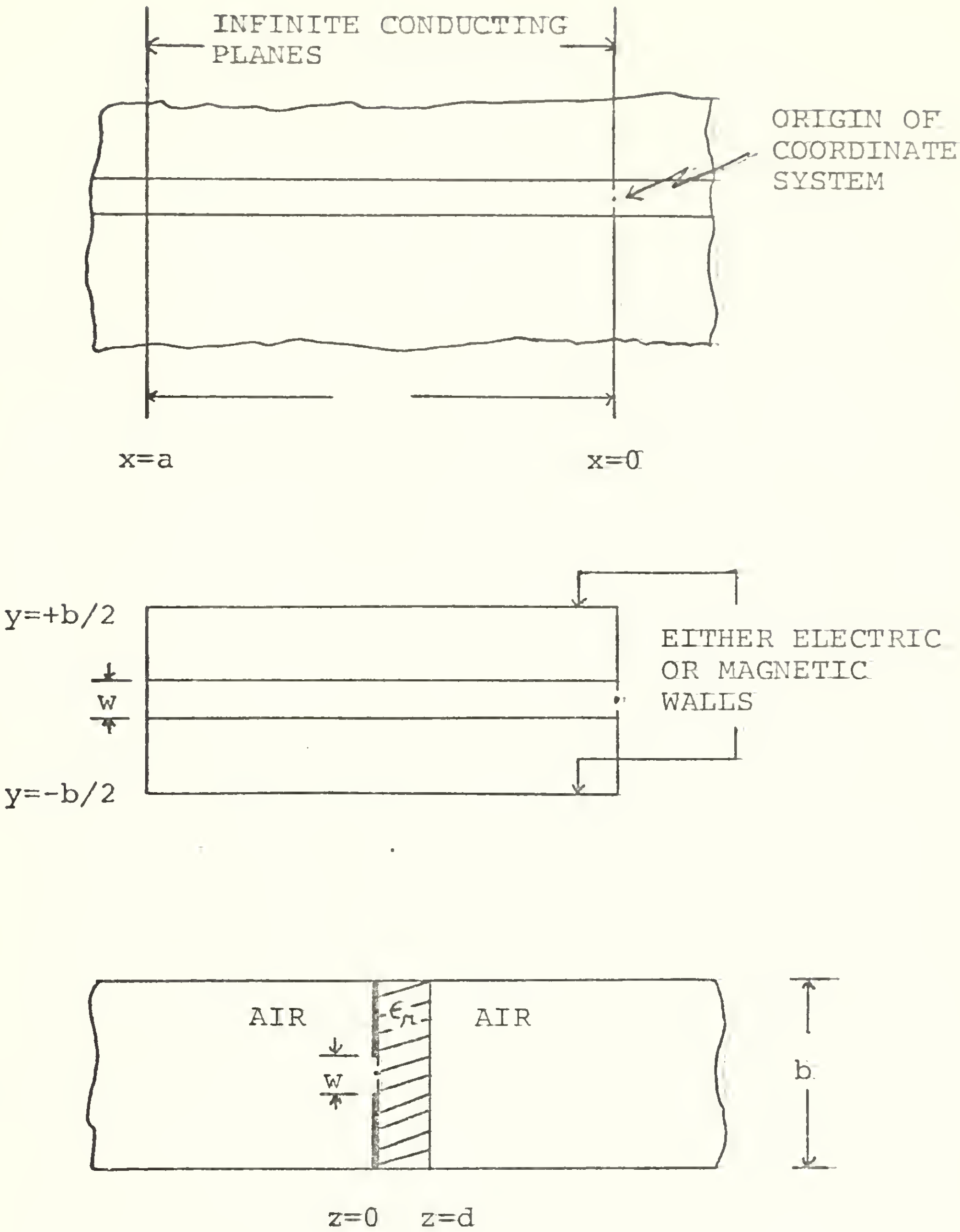


Figure 4. Slot Line as a Capacitive Iris and a Dielectric Slab in a Rectangular Waveguide.

$$u = \sqrt{\varepsilon_r - p^2} , \qquad v = \sqrt{p^2 - 1} \tag{4}$$

$$F_n = \sqrt{1 + \left(\frac{b}{2an} \cdot \frac{v}{p}\right)^2} , \quad F_{n1} = \sqrt{1 - \left(\frac{b}{2an} \cdot \frac{u}{p}\right)^2} \tag{5}$$

$$\delta = w/b \qquad \eta = 376.7 \text{ ohms per square}$$

For F_{n1} real:

$$M_n = \frac{\varepsilon_r \tanh r_n - p^2 F_{n1}^2 \coth q_n}{\left[1 + \left(\frac{b}{2an}\right)^2\right] F_{n1}} - u^2 \tag{6}$$

Where:

$$r_n = \frac{2\pi n d F_{n1}}{b} + \tanh^{-1} \left(\frac{F_{n1}}{\varepsilon_r F_n}\right) \tag{7}$$

$$q_n = \frac{2\pi n d F_{n1}}{b} + \coth^{-1} \left(\frac{F_n}{F_{n1}}\right) \tag{8}$$

For F_{n1} imaginary:

$$M_n = \frac{\varepsilon_r \tan r_n' - p^2 |F_{n1}|^2 \cot q_n'}{\left[1 + \left(\frac{b}{2an}\right)^2\right] |F_{n1}|} - u^2 \tag{9}$$

Where:

$$r_n' = \frac{2\pi n d |F_{n1}|}{b} + \tan^{-1} \left(\frac{|F_{n1}|}{\varepsilon_r F_n}\right) \tag{10}$$

$$q_n' = \frac{2\pi nd|F_{n1}|}{b} + \cot^{-1}\left(\frac{F_n}{|F_{n1}|}\right) \tag{11}$$

The complete derivation of Eq. 3 and a similar equation for magnetic walls at y=±b/2 is given in [Ref. 5]. In addition the derivations of Eq. 12 for the ratio of phase velocity to group velocity and Eq. 13 for the characteristic impedance Z_o are given in the same reference.

$$\frac{v}{v_g} = 1 + \frac{f}{\lambda'/\lambda} \cdot \frac{-\Delta(\lambda'/\lambda)}{\Delta f} \tag{12}$$

$$Z_o = 376.7 \frac{v}{v_g} \frac{\pi}{p} \cdot \frac{\Delta p}{-\Delta \eta B_t} \text{ ohms} \tag{13}$$

The above equations have been used to produce a set of normalized slot line design graphs [Ref. 6] for selected values of substrate permittivity with "d" and "w" as parameters.

Reference 7 gives the slot line field components, derived by mode summation techniques, for the various air and dielectric regions.

C. TRANSITIONS

Experimental results [Refs. 2, 8] with slot line have shown that a slot wave impedance of approximately 75 ohms is necessary to match a 50 ohm TEM system. Two reasons have been suggested for this apparent discrepancy [see Ref. 9]. First because of the transitions used a

mode/impedance transformation takes place and secondly, because of the non-TEM nature of the slot wave the characteristic impedance, ($Z_o = V^2/P$) as defined by Cristal et al [Ref. 1] is not unique.

Theoretical solutions of the coaxial line to slot line transition and of the microstrip to slot line transition are given in [Ref. 9].

III. THE VSWR JIG

The first design and construction of a jig for measuring slot line VSWR consisted of a piece of 1.5 inch thick aluminum stock 4 inches by 14.5 inches with a 12-inch by 2.5-inch center section removed. A horizontal slot was cut along the longer dimension and a brass sliding probe assembly was installed.

The probe consisted of a 4-inch piece of 85 mil semirigid coaxial cable, with 0.125 inches of the center conductor bared. The probe was terminated with a HP-440A crystal detector.

The probe assembly was made variable in three dimensions in order to accommodate slot lines of various dimensions. Horizontal probe travel was 12.5 inches, vertical prove travel was 0.5 inches and travel in the "y" dimension of the slot was 0.75 inches.

A. TESTING THE JIG

Initial tests of the jig were conducted on an II-inch slot line constructed from Custom High-K 707-20 of the following dimensions: b=2 inches, w=0.28 inches ± 0.002 inches, d=0.055 inches. The input and output transitions were made with 85 mil semirigid coaxial cable and the output cable was terminated in a 50 ohms load. Time-Domain Reflectometry (TDR) was the method used in evaluating the usefulness of the jig.

When the slot line was clamped in the VSWR jig, a decrease in the slot line characteristic impedance was observed corresponding to a relative change in reflection coefficient of approximately 0.1. In addition, an oscillatory waveform was observed over the entire length of the line.

These problems were overcome by removing a 12-inch section of metal opposite the probe assembly and replacing it with phenolic sliding arms and plexiglass clamps. The change in reflection coefficient between the mounted and unmounted line was then less than 0.005 and the waveform oscillations were eliminated.

The probe was then mounted and TDR tests were conducted to observe the perturbing effects of the probe. No record was made of these first observations but probe effects were almost negligible even with the probe at the closest possible position above the slot. Since this first jig was rather crude mechanically it was decided to construct a modified version before making any VSWR measurements.

B. THE FINAL JIG

The basic design of the final jig was similar to the one described above, utilizing the phenolic rods with plexiglass clamps to hold the slot line. Vertical probe travel was extended to 1.5 inches, "y" dimension travel was extended to 2 inches. Horizontal travel was essentially the same, but a screw drive system was provided for horizontal positioning of the probe assembly. This type of drive system

tended to make data taking more tedious since rapid positioning of the probe was not possible. (Facilities for making a suitable rack and pinion drive were not available). Legs 3.5 inches in height were provided to further isolate the line from capacitive effects. A metric scale and a ten-division vernier provided measurement capability of 0.1 mm. Figure 5 shows the final jig with a slot line mounted for measurements. Figure 6 shows another view of the final jig without the slot line.

C. FINAL TESTING OF THE JIG

TDR observations were again used as the method of evaluation. Figure 7 shows typical TDR observations of a slot line mounted in the VSWR jig with the probe removed. Figure 8 shows TDR observations of the same line but this time the probe was positioned for VSWR measurements.

Figure 9 shows the actual vertical and "y" positioning of the probe. The cable outer conductor is shown in contact with the metal covering the substrate. This vertical positioning was used because it was impossible to construct a completely flat slot line with the materials available.

The settings of the TDR for the observations of Figs. 7 and 8 show a relative change in reflection coefficient of approximately 0.005.

Later an additional test was conducted with the slot line terminated in a HP-477B thermistor mount. Power meter readings taken with a HP-430c Microwave Power Meter

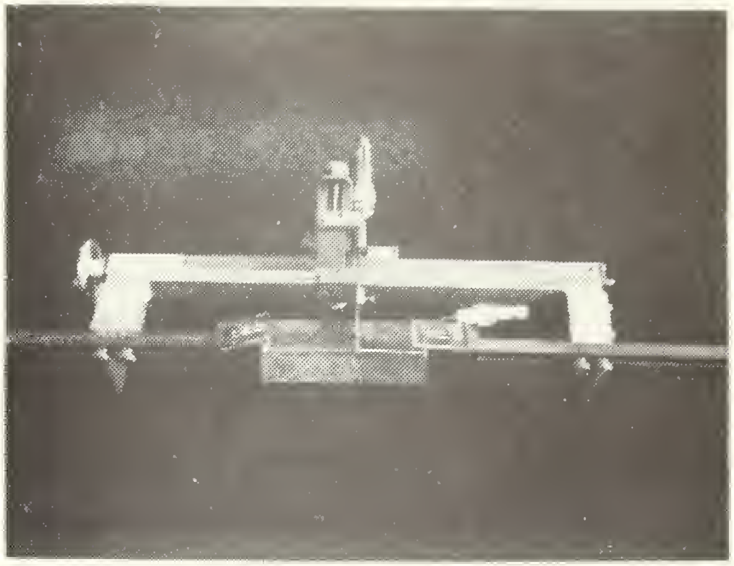


Figure 5. Slot Line Mounted in VSWR Jig.

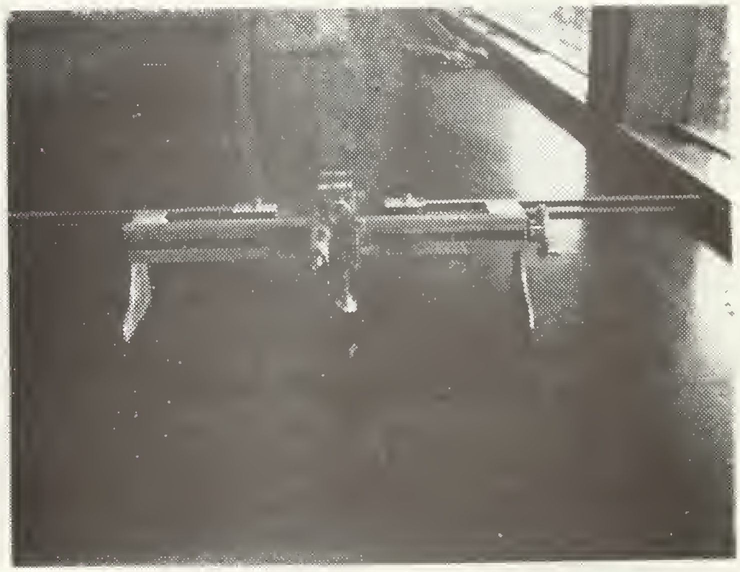


Figure 6. VSWR Jig.

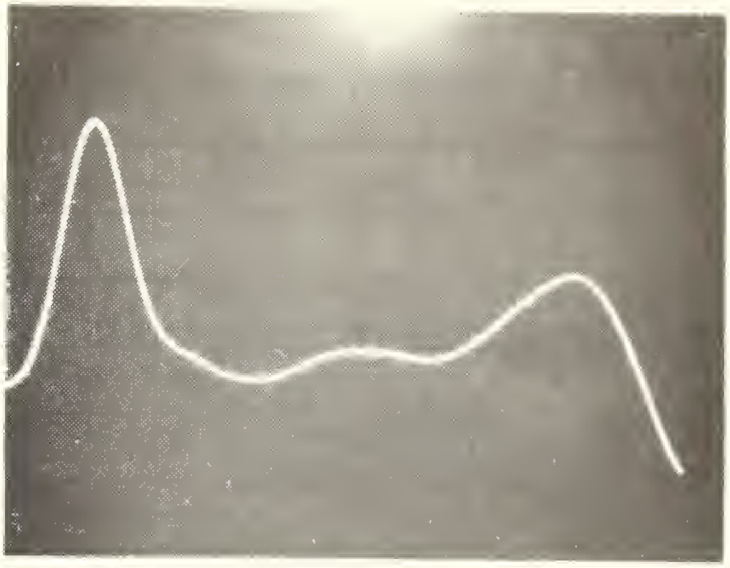


Figure 7. TDR Observation of Slot Line Mounted in VSWR Jig, with Probe Removed.

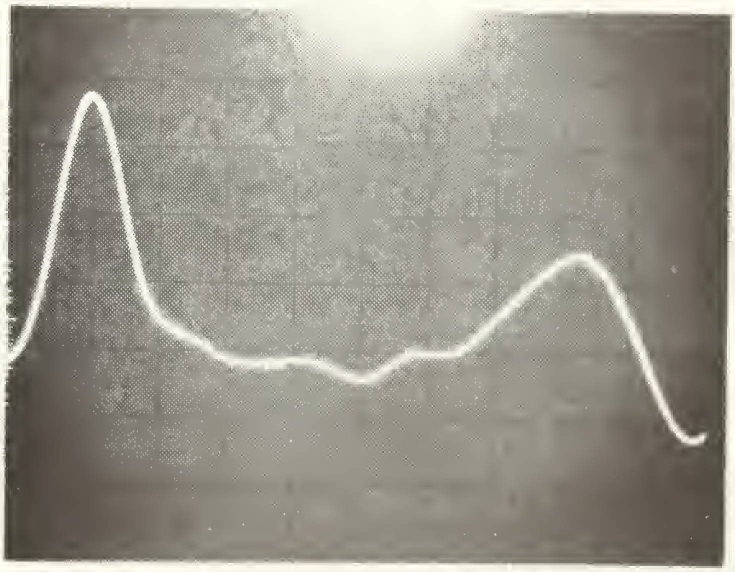


Figure 8. TDR Observation of Slot Line Mounted in VSWR Jig, with Probe Positioned for Measurements.

showed no change in power level when the detector probe was in position for measurement or when it was removed. This test was conducted at several frequencies between 4GHz and 7GHz.

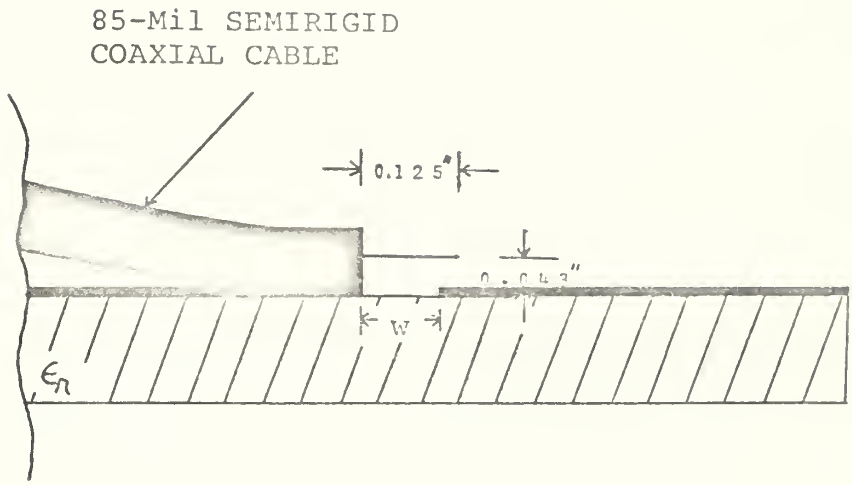


Figure 9. Probe Position Relative to the Slot.

IV. FABRICATION OF SLOT LINE

While making the final evaluations of the VSWR jig a significant difference was observed between experimental values of λ' and the theoretical values specified by the design graphs of [Ref. 6]. A considerable amount of time was spent on slot line fabrication in an attempt to explain this discrepancy in values of λ'.

All of the slot lines tested in the Thesis were constructed from the same piece of Custom High-K707-20, which was purchased in a one-square-foot section, one-eighth inches thick and clad with two-ounce copper on both sides. Measurement of the dielectric constant using cavity perturbation techniques showed agreement within 2.5 percent of the specified value. Mariani et al [Ref. 8] have stated that a change of this magnitude in substrate permittivity would produce only a 1.25 percent change in λ'/λ ratios.

Originally it was intended to construct a line 11 inches in length, 2 inches in width, and a substrate thickness of 0.055 inches. These dimensions would allow operation in the 3GHz to 12GHz frequency range. The slot width was chosen to provide approximately 75 ohm slot wave impedance in the center of this frequency range. (These slot widths were not always obtained.)

Attempts at machining the substrate were initially disastrous. Removal of the copper from one side of the substrate caused the material to warp appreciably and

because of the brittleness of the substrate it cracked in several places while it was being milled. The copper was then etched from both sides of the substrate and the substrate was then able to be sanded to the desired thickness of 0.055 inches ±0.002 inches.

A. PRESSURE SENSITIVE ADHESIVES

Scotch brand Copper tape No. X-1181 with a pressure-sensitive conductive adhesive was applied to the substrate and a 28 mil slot was cut in the copper using a scalpel. A single coaxial line to slot line transition was made at the input. (This is the same line that was used in the initial TDR tests of the VSWR jig.) Short-circuit and open-circuit measurements of λ' using the VSWR jig showed wavelengths exceeded theoretical values by approximately 30 percent. Since it is extremely difficult to cut a slot in the metal coating without also cutting the substrate slightly (<2 mils) the copper tape was removed and the substrate sanded to remove the cuts.

Several photographic positives were made by applying lines of black circuit tape to a white background and then photographically reducing them to produce desired slot widths. This procedure provided excellent line definition.

The substrate after sanding was 52 mils ±2 mils in thickness and 8.75 inches in length. (Breaking of pieces of the substrate was a continuing hazard since all processing was done by hand.) The width of the substrate remained unchanged.

Circuit-Stik copper foil with a non-conductive pressure sensitive adhesive was applied to the substrate and a 26 mil slot was photoetched in the copper. This slot line was tested using the same set-up as before, and experimental results of λ' measurements were again greater than theoretical values by as much as 30 percent.

In all of the photoetched slots that were constructed, the definition of the slot was generally very good, but the width of the slot was two to four mils narrower than the photographic positive. This was believed to have been caused by light leakage during the processing.

When copper with a pressure sensitive adhesive was applied to the substrate it was impossible to achieve a smooth copper covering due to flaws in the adhesive coating. When a slot was photoetched in copper that had a conductive adhesive it was necessary and difficult to remove the adhesive from the slot after the etching process. A solvent such as acetone proved best for this task. In the case of the non-conductive adhesive neither removal of the adhesive from the slot nor leaving it in the slot produced any significant differences in slot wavelength.

B. VACUUM EVAPORATION

It was now believed that the reason for the large disagreements between experimental and theoretical values of λ' was probably attributable to the adhesives used on the copper foil. In an effort to confirm these suspicions five

attempts were made to deposit copper on the substrate by evaporating it in a high vacuum chamber. However, because of the unavailability of a large "boat" it was not possible to deposit a layer of copper more than a few microns in thickness before the vacuum had to be broken and more copper had to be placed in the "boat".

The breaking of the vacuum allowed oxidation of the copper that had just been evaporated on to the substrate. These oxidation layers allowed the copper to separate in layers. A single evaporation of copper on to the substrate was too thin for soldering transitions even with indium. Because of the limited time available the evaporation process was abandoned without acquiring the desired slot line data.

It can be concluded from the small amount of experimentation that was performed that this method of slot line construction appears to offer great promise. If a slot mask is placed on the substrate, the need for photoetching or cutting of a slot is eliminated. Aluminum with its better adhesive qualities can be deposited on the substrate at much lower temperature and lower cost.

When aluminum is used for the metallization, a conductive epoxy will be necessary for making the coaxial line to slot line transition, or a different type of transition may be developed.

C. USING THE COPPER CLAD SUBSTRATE

It was decided to construct a slot on a three inch by four inch copper clad (as purchased) substrate. The copper was removed from one side of the material and (the warp of this short line was neglected) a 54 mil slot was photo-etched on the other side. The actual substrate thickness after removal of the copper and adhesive was 117 mils ±1 mil. Experimental values of the λ'/λ ratio for this slot line were in agreement with theoretical values by 2.5 to 4 percent.

The copper was removed from both sides of another three inch by four inch by 0.117 inch substrate and the Circuit-Stik copper foil with non-conductive adhesive was applied to one side. An 80 mil ±5 mil slot was cut in the copper foil. Experimental values of the λ'/λ ratio were 6 to 11 percent greater than theoretical values for the line.

D. SLOT LINE FABRICATION CONCLUSIONS

One possible explanation for the large disagreement between measured and theoretical values of λ' in some instances and the acceptable difference in other instances is that the ratio of adhesive thickness to substrate thickness for the 117 mil thick substrate is approximately 0.0068 while for a substrate 44 mils thick the ratio is approximately 0.018. This larger ratio for the thinner substrate probably results in a lower effective dielectric constant with a corresponding increase in λ'. Since no

proof was available to substantiate these suspicions, the need is evident for a continuing investigation in methods of slot line construction and measurement techniques.

Mariani et al [Ref. 8] have reported very good agreement between experimental and theoretical values of λ' using copper plated substrates. For substrates covered with aluminum sensing tape the agreement is not as good. The substrates were also 20 mils to 90 mils thicker than the 44 mil substrate reported on in this Thesis. The adhesive layer was also much thinner on the aluminum tape.

V. MEASUREMENTS OF SLOT WAVELENGTH

Measurements of slot wavelength, λ', were made using the jig designed for VSWR measurements. Several minima were observed, (from 2 to 20) over the length of the line at a given frequency and averaged to provide the values of λ'. These measurements were made with the slot line open circuited and again with the line short circuited. The measurements were made with and without transitions. The measurements were repeated as vertical probe distances were varied from 0 to 0.5 inches. The results in all cases were essentially the same.

Tables I-IV show the experimental values of λ'/λ and the percentage difference from theoretical values. Figures 10-13 show the data graphically. In these figures the experimental values are seen to lie approximately parallel to the theoretical curves but in all cases these experimental values are greater than the theoretical values.

TABLE I

Description	Frequency GHz	λ'/λ Experimental	λ'/λ Theoretical (from Design Graphs)	Percent Difference
$\varepsilon_r=20$				
Custom High-K-707-20				
w=0.054" ± 0.002"	2	0.376	0.362	+3.87
d=0.117" ± 0.001"	3	0.355	0.344	+3.20
w/d=0.462	4	0.339	0.330	+2.73
b=3.63"	5	0.328	0.318	+3.14
ℓ=3.95"	6	0.316	0.306	+3.27
Copper clad as purchased (2 oz. copper)				

TABLE II

Description	Frequency GHz	λ'/λ Experimental	λ'/λ Theoretical (from Design Graphs)	Percent Difference
$\varepsilon_r=20$				
Custom High-K-707-20				
w=0.017" ± 0.002"	3	0.478	0.383	+24.80
d=0.044" ± 0.002"	4	0.465	0.371	+25.34
w/d=0.386	5	0.462	0.361	+27.98
b=1.87"	6	0.444	0.354	+25.42
ℓ=4.44"	7	0.441	0.347	+27.09
	8	0.432	0.341	+26.69
Circuit-Stik	9	0.429	0.336	+27.68
Copper Foil	10	0.420	0.330	+27.27
with conductive	11	0.414	0.326	+26.99
adhesive	12	0.408	0.322	+26.70

TABLE III

Description	Frequency GHz	λ'/λ Experimental	λ'/λ Theoretical (from Design Graphs)	Percent Difference
ε_r=20				
Custom High-K-707-20				
w=0.080" ± 0.005"	2	0.406	0.374	+8.56
d=0.117" ± 0.001"	3	0.376	0.341	+10.26
w/d=0.684	4	0.356	0.334	+6.59
b=3.59"	5	0.340	0.320	+6.25
ℓ=3.84"	6	0.324	0.306	+5.88
Circuit-Stik				
Copper Foil				
with non-conductive				
adhesive				

TABLE IV

Description	Frequency GHz	λ'/λ Experimental	λ'/λ Theoretical (from Design Graphs)	Percent Difference
ε_r=20				
Custom High-K-707-20				
w=0.031" ± 0.001"	4	0.453	0.390	+16.15
d=0.044" ± 0.002"	5	0.442	0.379	+16.62
w/d=0.705	6	0.432	0.368	+17.40
b=1.87"	7	0.424	0.360	+17.77
ℓ=4.44"	8	0.413	0.352	+17.33
Circuit-Stik	9	0.408	0.346	+17.92
Copper Foil	10	0.400	0.338	+18.34
with non-conductive	11	0.392	0.332	+18.07
adhesive	12	0.388	0.327	+18.65

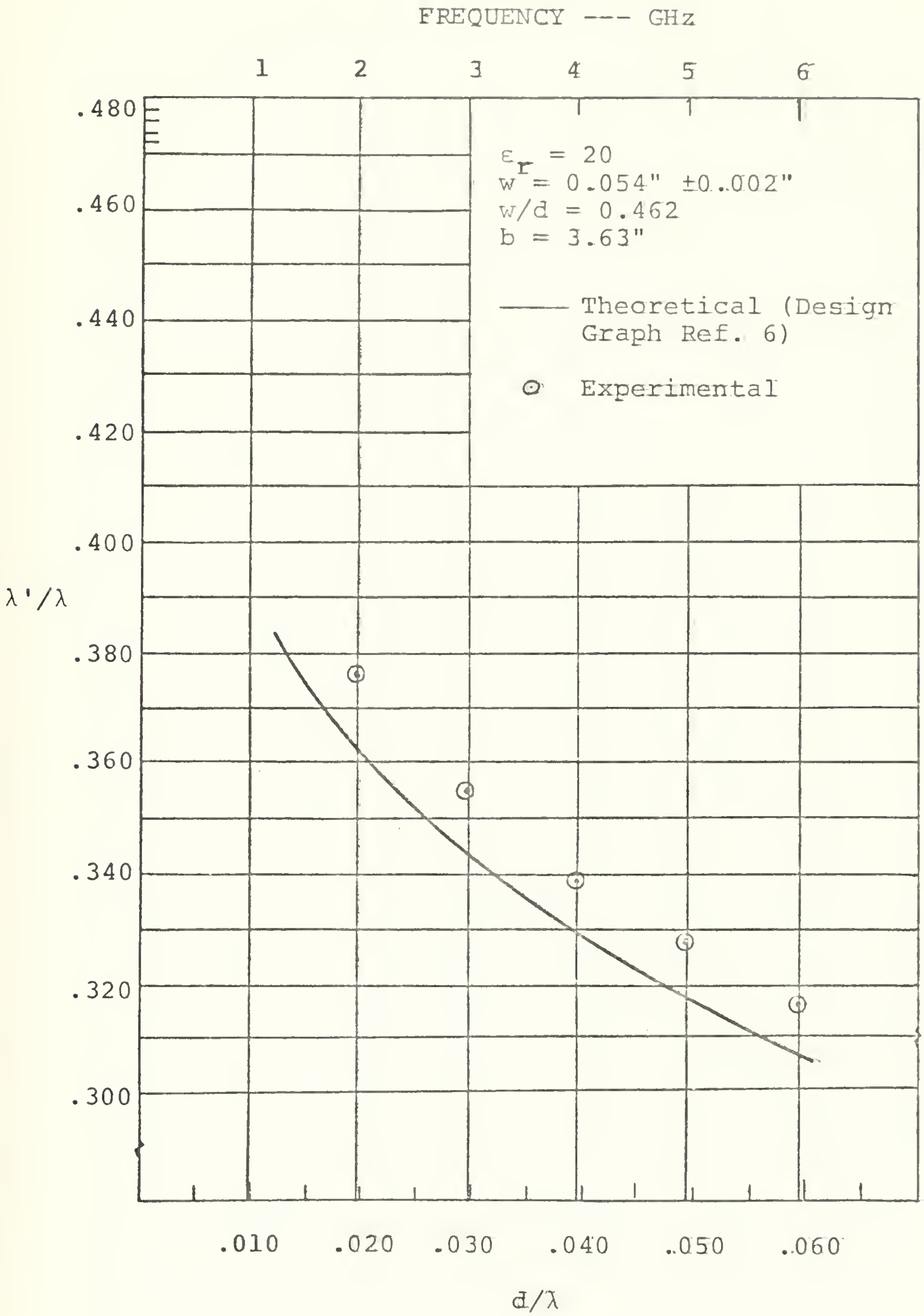


Figure 10. Experimental and Theoretical Values of λ'/λ.

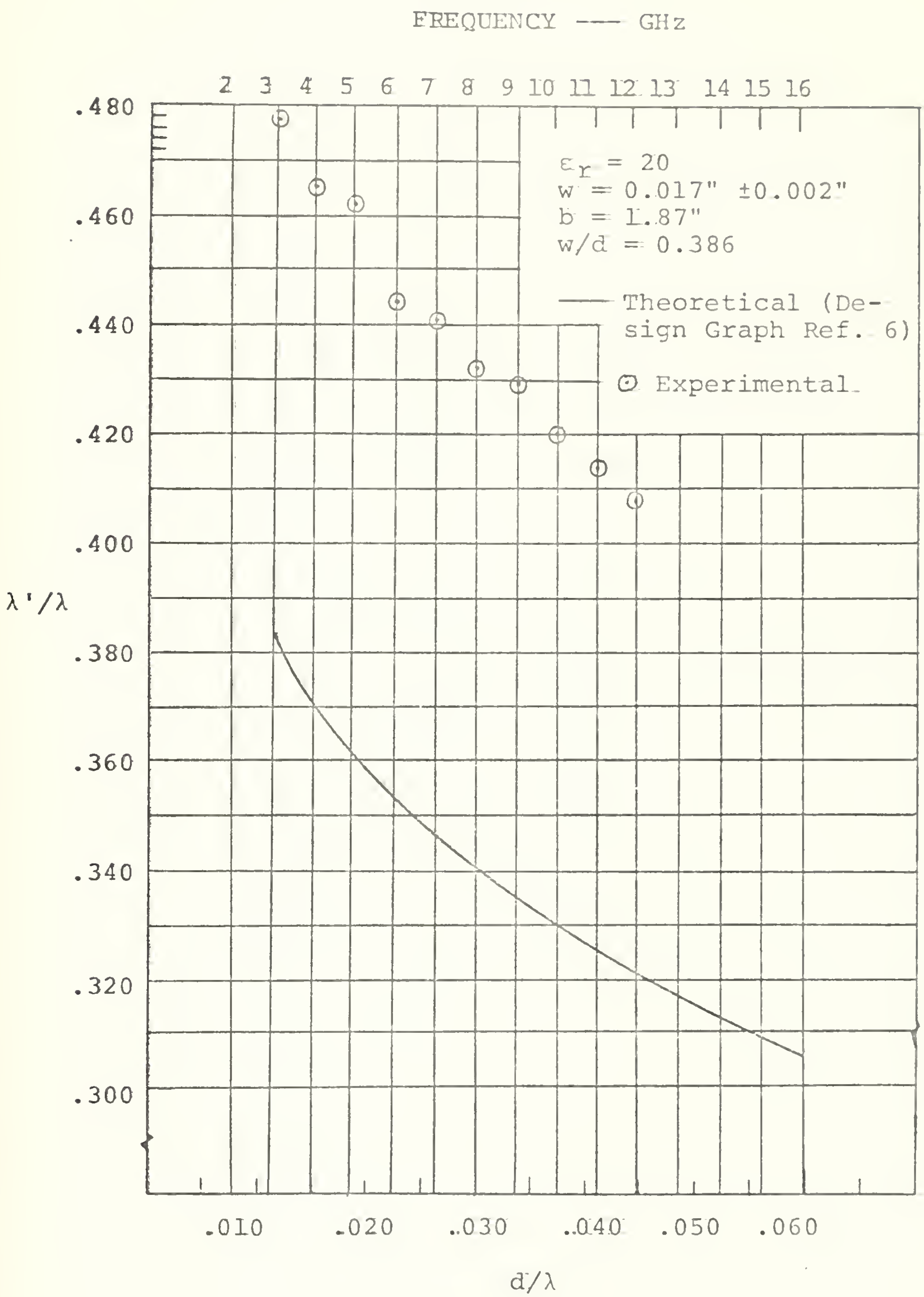


Figure 11. Experimental and Theoretical Values of λ'/λ.

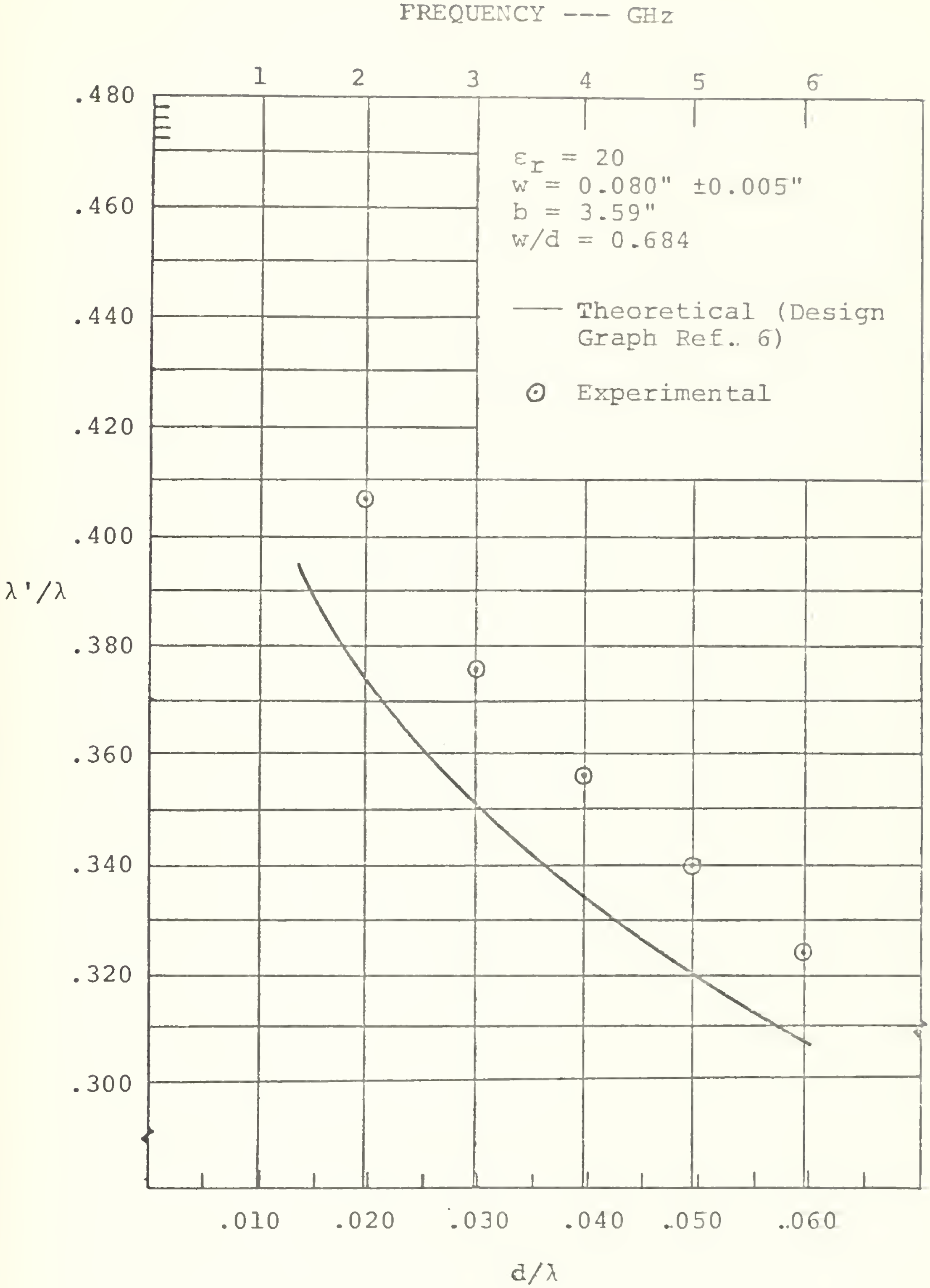


Figure 12. Experimental and Theoretical Values of λ'/λ.

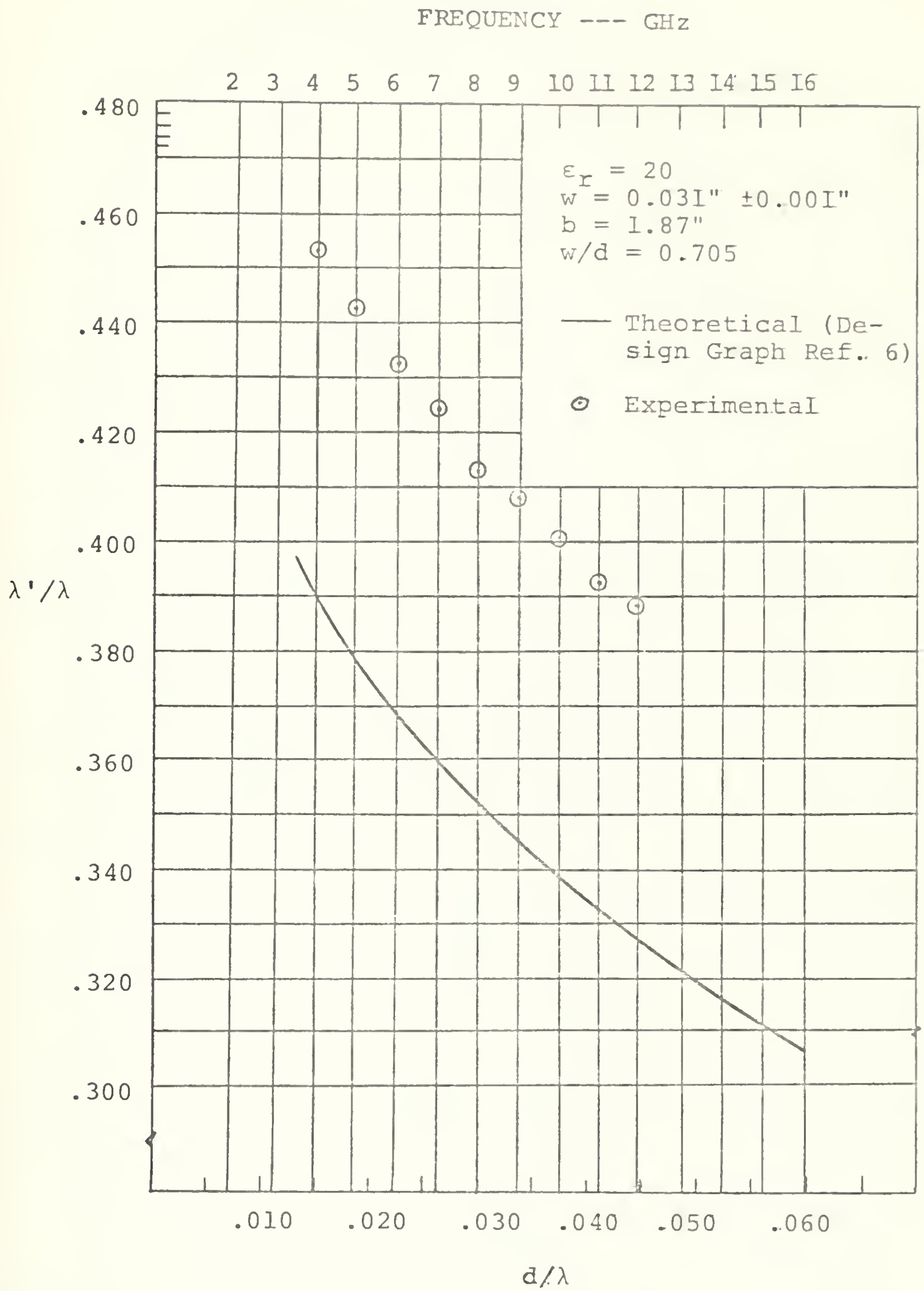


Figure 13. Experimental and Theoretical Values of λ'/λ.

VI. MEASUREMENT OF VSWR

VSWR measurements were made on three different slot lines utilizing two different transitions. The first type of transition was a coaxial line to slot line transition (all input transitions were of this type) utilizing either 141 mil or 85 mil semirigid coaxial cable. The second type of transition was a 50 ohm load directly terminating the line as shown in Fig. 14.

This transition is quite similar to the coaxial line transition. An attempt was made to terminate the line directly with a wedge of microwave absorbant but this effort was unsuccessful.

The coaxial line transition terminated in a 50 ohm load was used with the 117 mil thick slot line and the transition of Fig. 14 was used to terminate the two 44 mil thick lines tested.

Figure 15 shows the results of a theoretical and experimental coaxial line to slot line transition as reported in [Ref. 9]. VSWR measurements using a 141 mil coaxial line transition terminated in a 50 ohm load are shown in Fig. 16. Figures 17 and 18 show the measured VSWR using the transition shown in Fig. 14.

The measurements were made using a HP-8690B signal source and the VSWR jig described in a previous section.

The Roberts and von Hippel [Ref. 10] method of measuring VSWR was used as a check of several indicated values, picked at random, and was in complete agreement.

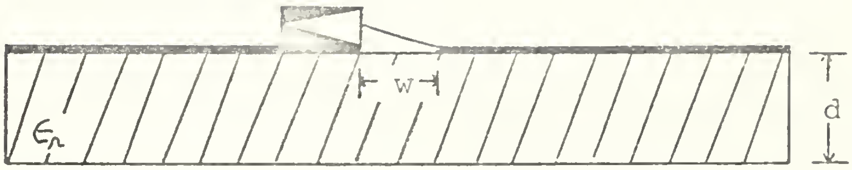


Figure 14. A 50 ohm Load Terminating the Slot Line.

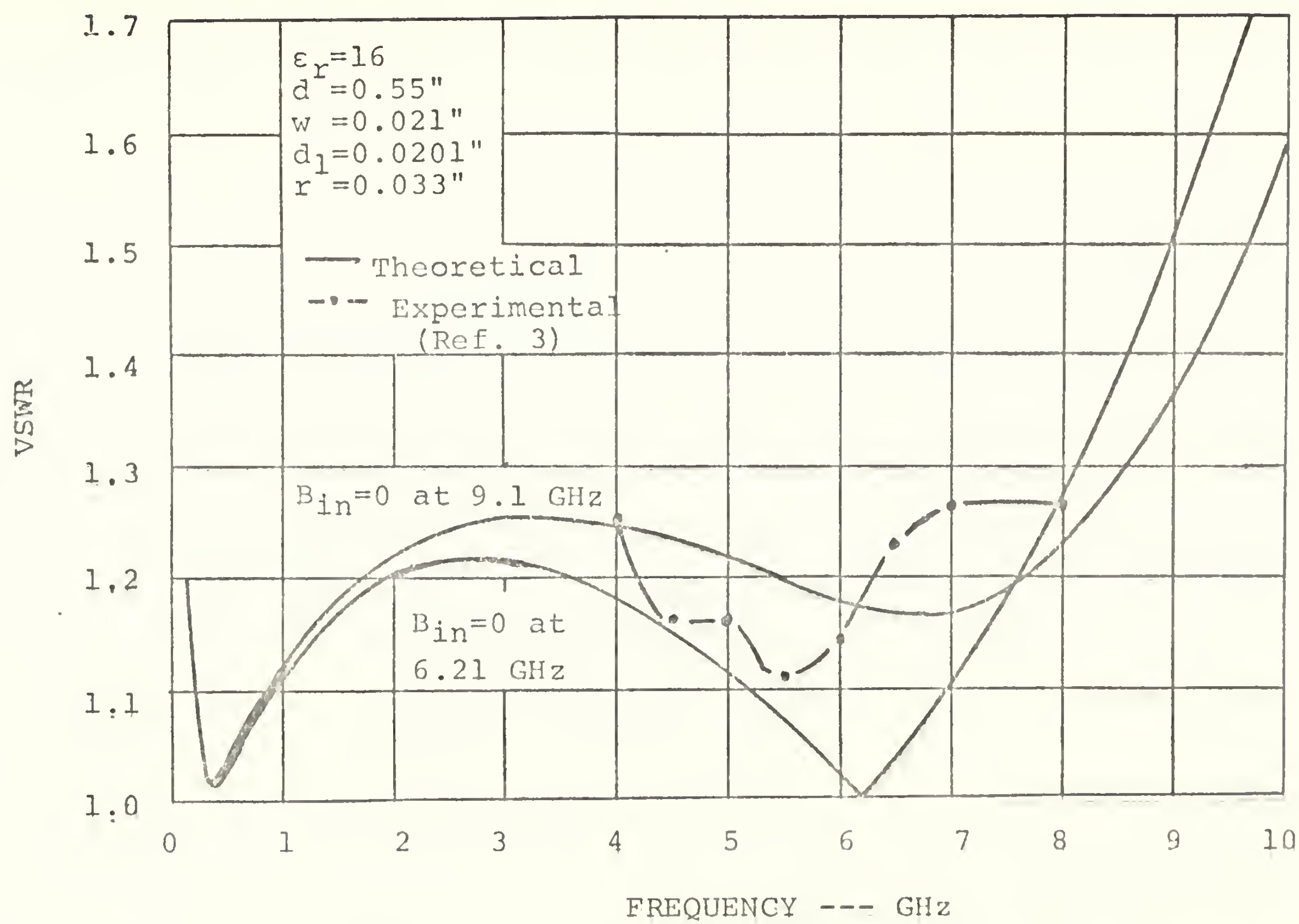


Figure 15. Experimental and Theoretical Data for a Slot-to-Coax Transition Ref. 9.

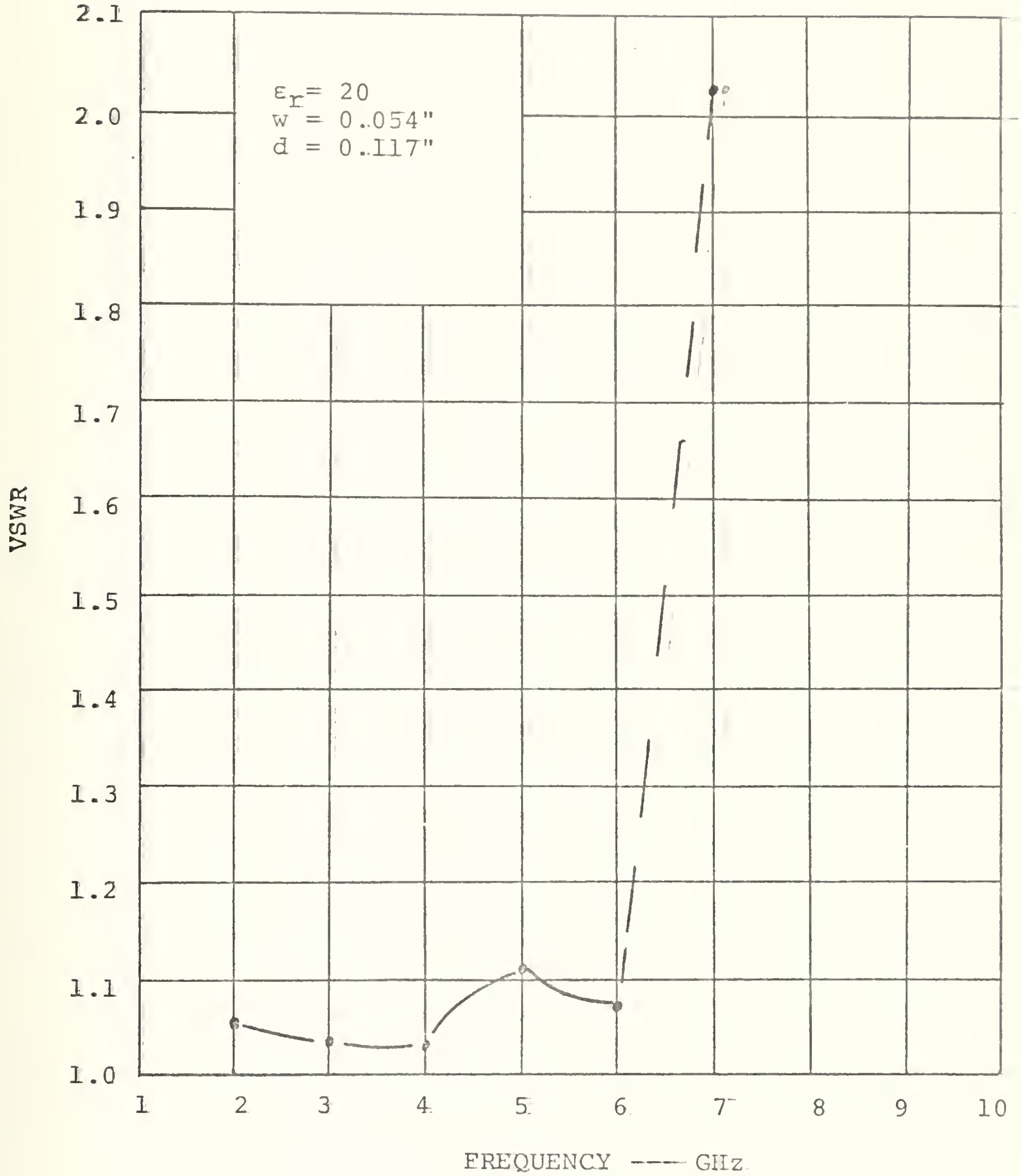


Figure 16. VSWR Using a Slot Line to Coaxial Line Transition.

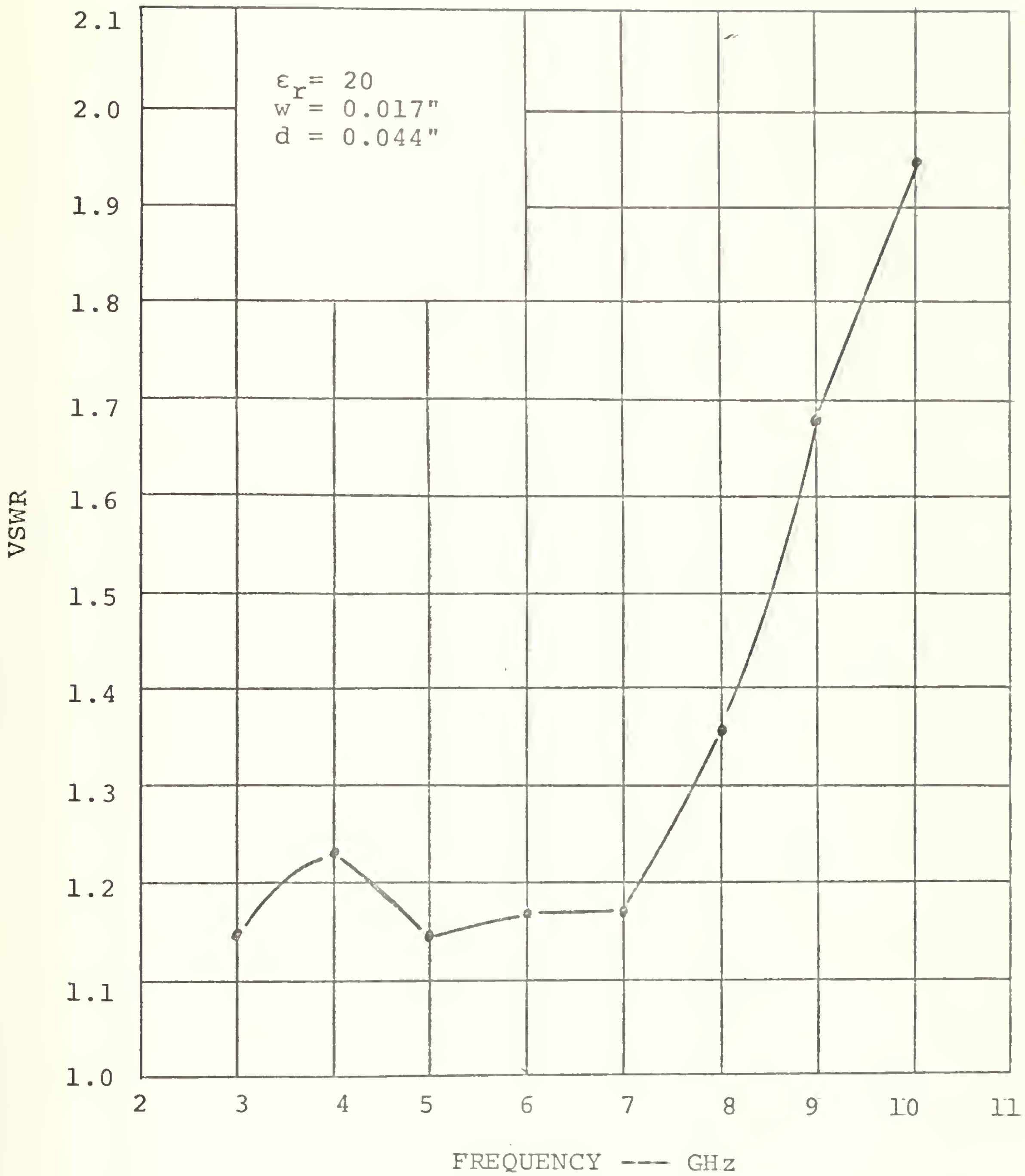


Figure 17. VSWR Using the Transition and 50 ohm Load Shown in Fig. 14.

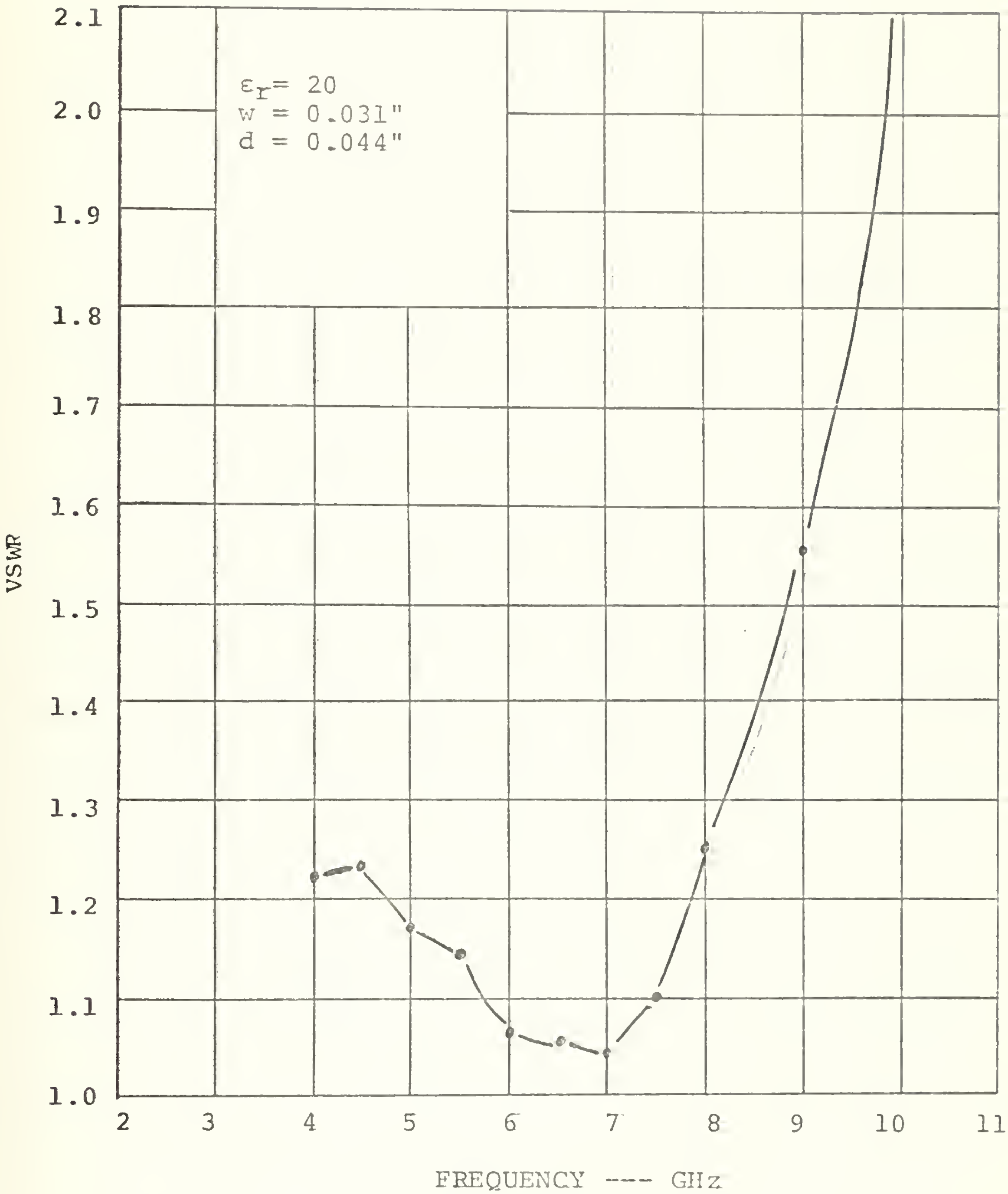


Figure 18. VSWR Using the Transition and 50 ohm Load Shown in Fig. 14.

VII. CONCLUSIONS

The slot line appears to be a very promising alternative to microstrip for use in microwave integrated circuti applications. However, it is evident that more research is necessary in slot line construction techniques, measurement techniques, mounting techniques and transitions. In addition, design criteria is needed for proposed applications such as phase shifters, circulators, and the mounting of shunt circuit elements.

Several slot lines were constructed using adhesive backed copper foil (both conductive and non-conductive adhesives) in order to examine the effects of the adhesive on slot wavelength. On all of the lines tested, the measured wavelengths were found to be greater than the theoretical values taken from the design graphs of Ref. 6. The increase in slot wavelength was also seen to be more pronounced for larger adhesive thickness to substrate thickness ratios.

Metalization by vacuum evaporization has been suggested as a promising method for use in slot line construction, since the adhesive effects would be eliminated and the entire fabrication could be made a one-step process.

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13. ABSTRACT

The slot line, since it was first proposed by Cristal et al [Ref. 1] in 1968, has been the subject of a continuing research effort in the microwave field. Some of this research effort is described herein, including difficulties encountered in slot line fabrication, and the design and construction of a slot line VSWR jig. Measurements of slot wavelength are presented with a comparison made to theoretical values. The results of VSWR measurements are also presented. Experimental work was performed in the 1GHz to 12GHz frequency range.

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